RF LABORATORY INSTRUMENTATION

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SUMMARY

- Recap of dB formalism and scattering parameters
- Time domain measurements
  - Digital oscilloscope
- Frequency domain measurements
  - Spectrum Analyzer (SA)
  - Vector Network Analyzer (VNA, or simply NA)

CONVERSION TO DB SCALE

- A convenient form to express large power or voltage ratios is the "*dB scale*"

$$dB = 20\ \log\left(\frac{V_2}{V_1}\right) = 10\ \log\left(\frac{P_2}{P_1}\right)$$

- When dB is given, the conversions are:

$$\frac{V_2}{V_1} = 10^{\mathrm{dB}/20} \quad \text{and} \quad \frac{P_2}{P_1} = 10^{\mathrm{dB}/10}$$

- Expressing voltage and power ratios in dB simplifies the algebra, since multiplication is reduced to addition and division to subtraction
- We use dB to simplify ratios. An absolute measure of power is given by the quantities dBm or dBW:

$$dBm = 10\ \log(P_{mW}) \ \Rightarrow\ 0\ dBm = 1\ mW$$
$$dBW = 10\ \log(P_W) \Rightarrow 0\ dBW = 1\ W$$

Power	1 μW	10 μW	.1 mW	1 mW	10 mW	.1 W	1 W	10 W	.1 kW	1 kW	10 kW	.1 MW	1 MW
dBm	-30	-20	-10	0	10	20	30	40	50	60	70	80	90
dBW	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60

2-PORTS NETWORK CHARACTERIZATION

Low frequency network characterization

Hybrid parameters

$$V_1 = h_{11}I_1 + h_{12}V_2$$
$$I_2 = h_{21}I_1 + h_{22}V_2$$

Admittance parameters

$$I_1 = y_{11}V_1 + y_{12}V_2$$
$$I_2 = y_{21}V_1 + y_{22}V_2$$

Impedance parameters

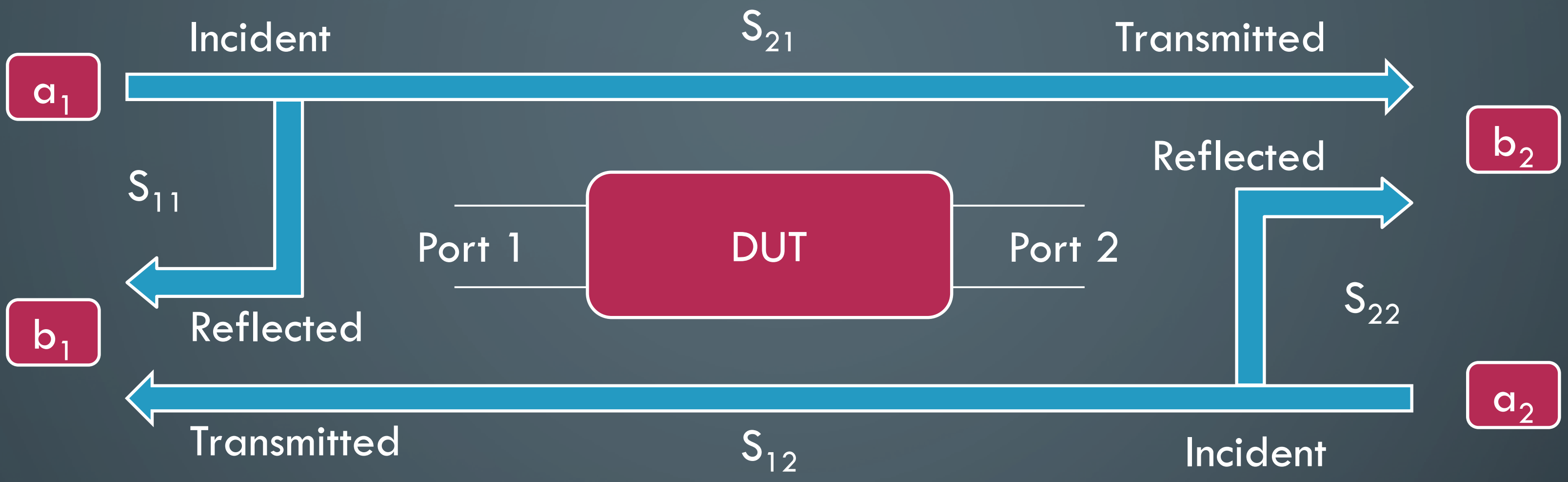
$$V_1 = z_{11}I_1 + z_{12}I_2$$
$$V_2 = z_{21}I_1 + z_{22}I_2$$

$$y_{12} = \left.\frac{I_1}{V_2}\right|_{V_1=0}$$

$$z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0}$$

- At high frequency is very hard to measure total voltage and current at the device ports
- A voltmeter or a current probe cannot be directly connected to get an accurate measurement, due to the impedance of the probe itself and the difficulty to correctly place the probe at the desired position
- In the case of a short circuit with a wire; the wire itself has an inductance that can be of substantial magnitude at high frequency. Also open circuit (I=0 condition at high frequencies is not obtained simply "opening" a circuit, due to irradiation…) leads to capacitive loading at the terminal
- In addition, active device may oscillate or even self-destruct when connected to short or open terminations!!!

SCATTERING PARAMETERS



For a 2 port device, two other independent equations may be written, which are function of incident (a) and reflected (b) waves:

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

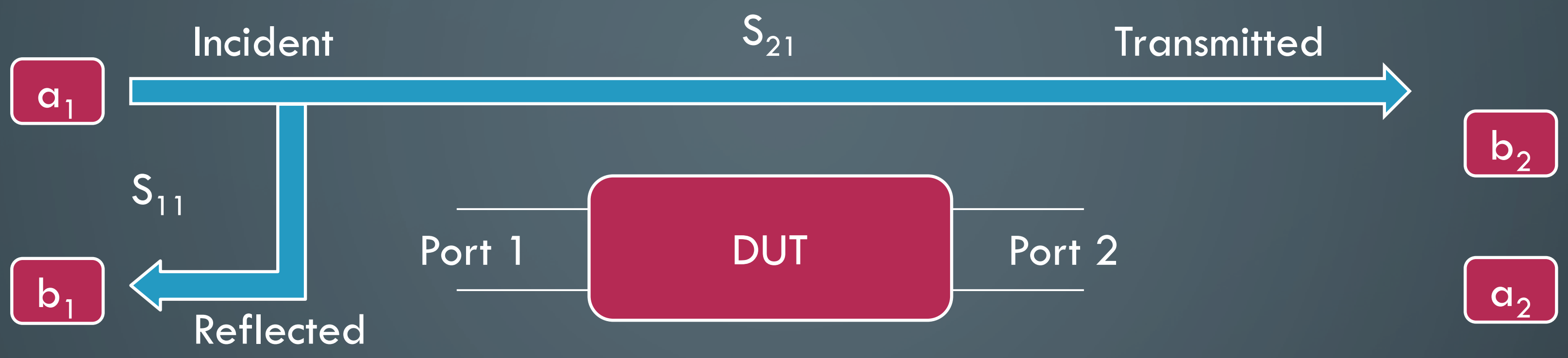
Where b_1 comprises the sum of a quantity reflected from port 1 and a quantity that is the result of the transmission trough the device in the reverse direction (and vice versa for b_2) .

These quantities are scaled to be proportional to the voltage wave amplitude and phase such that:

$|a_n|^2$= incident power on the n-th port

$|b_n|^2$= emerging power from the n-th port

MEASURING S PARAMETERS (1)



$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

$$\Rightarrow \quad S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$

Ideal matched load (Z_0) on port 2

- Related to familiar measurements: gain, loss, reflection coefficient
- Defined in terms of voltage travelling waves – relatively easy to measure at high frequencies
- No connection of undesirable loads to the DUT (short or open), but only matched loads
- Measured S parameters of multiple devices can be cascaded to predict overall system performance

SCATTERING PARAMETERS (2)

N-port device has N^2 scattering parameters

$S_{m\,n}$

m: port where signal emerges

n: port where signal is applied

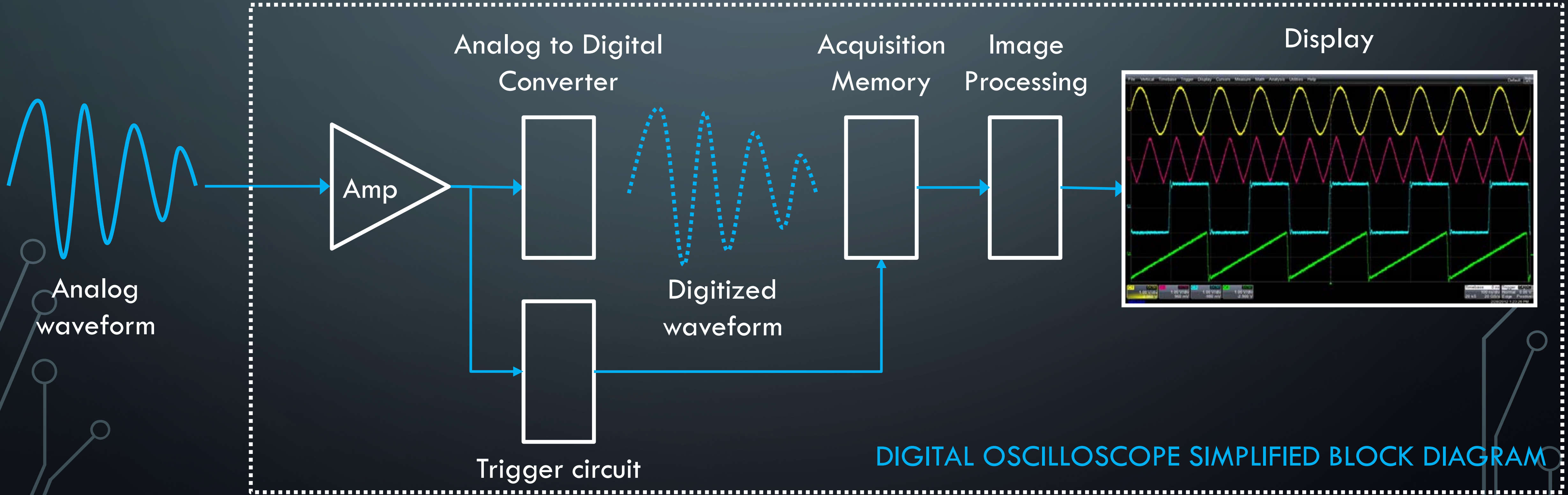
Parameter	Common measurement term
S_{11}	Forward reflection coefficient (input match)
S_{21}	Forward transmission coefficient (gain or loss)
S_{22}	Reverse reflection coefficient (output match)
S_{12}	Reverse transmission coefficient (isolation)

- S parameters are inherently complex, linear quantities. They are expressed as real-and-imaginary or amplitude-and-phase pairs
- However, often we want to look only at the magnitude of an S-parameter (e.g. when looking at insertion loss or input match), and often a logarithmic scale is more useful. A log-magnitude display let us see far more dynamic range than a linear format

TIME DOMAIN MEASUREMENTS

DIGITAL OSCILLOSCOPE

- One of the most common and intuitive device in a RF/electronics/particle physics LAB
- Signal characterization in time domain (amplitude vs time)
- Input signal is buffered and then A/D converted. Instrument BW and resolution depend on the front-end, ADC "quality" (n. of bits) and software efficiency
- Digital data stream is stored, processed and displayed according to experimental needs. For example: special digital signal algorithms allow smart triggering of the instrument



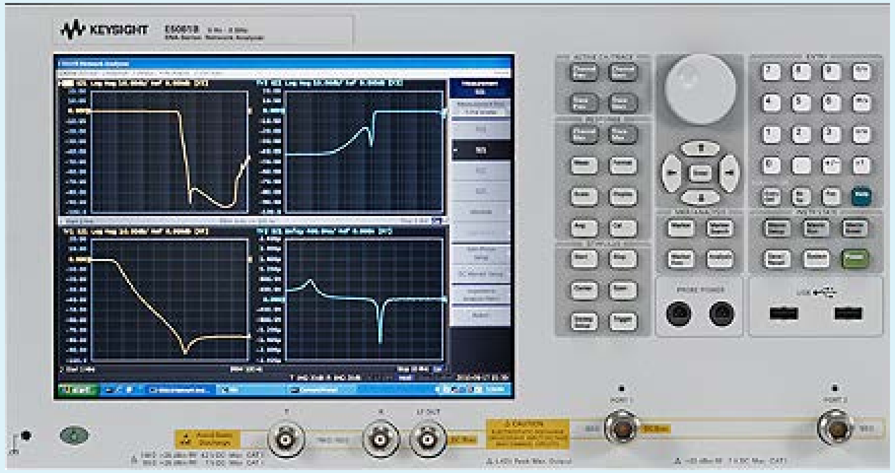
DIGITAL OSCILLOSCOPE SIMPLIFIED BLOCK DIAGRAM

FREQUENCY DOMAIN MEASUREMENTS

WHAT IS THE DIFFERENCE BETWEEN NETWORK AND SPECTRUM ANALYZERS?

NETWORK ANALYZERS

Amplitude ratio
Phase difference



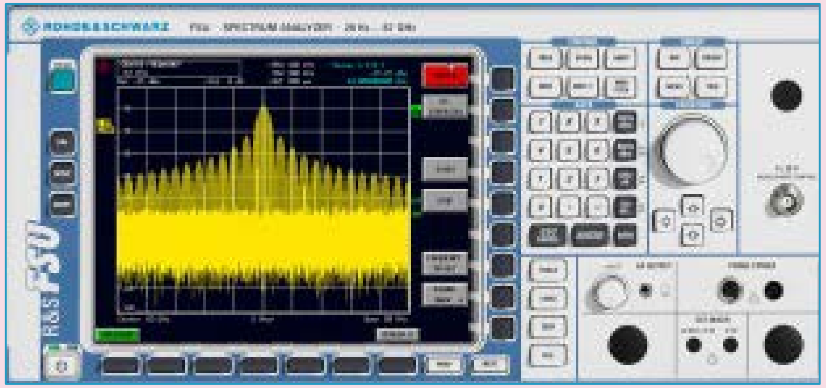
Frequency

Measure "known" signals (in terms of *frequency*)

- Characterize components, devices, circuits, sub assemblies and even accelerating structures
- Contain source and multiple receivers
- Display ratioed amplitude and phase (frequency or power sweeps)
- Hard to get an accurate trace, easy to interpret the results

SPECTRUM ANALYZERS

Power



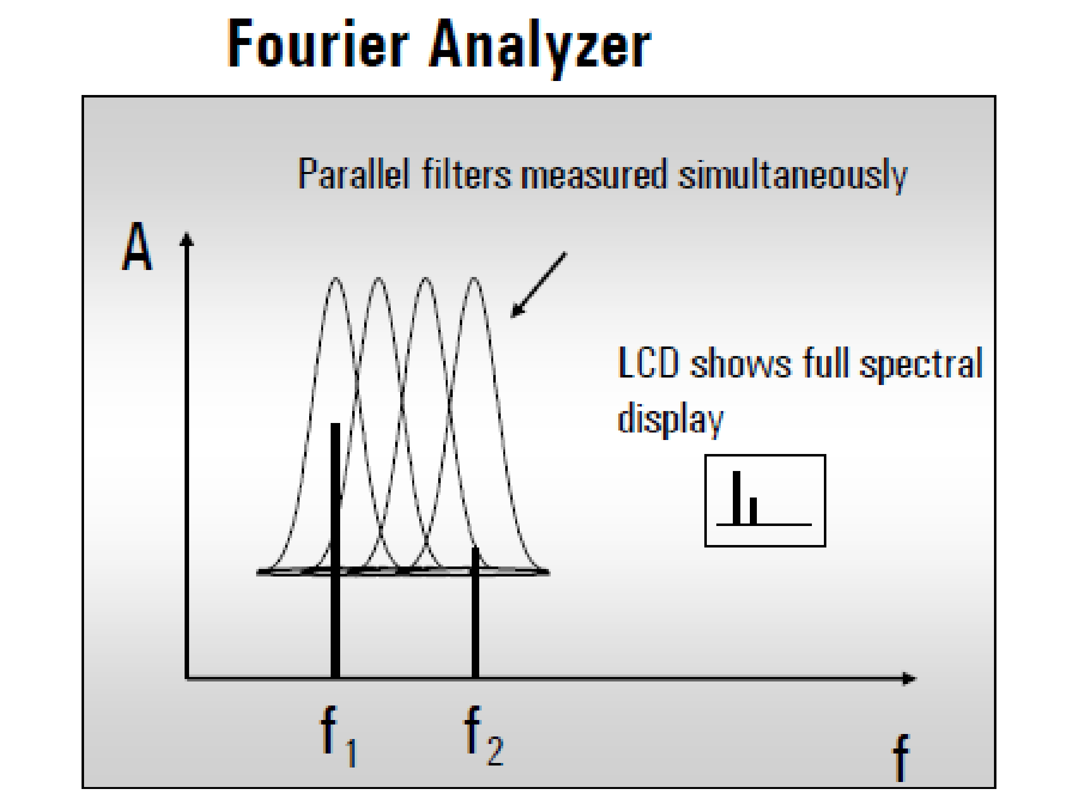
Frequency

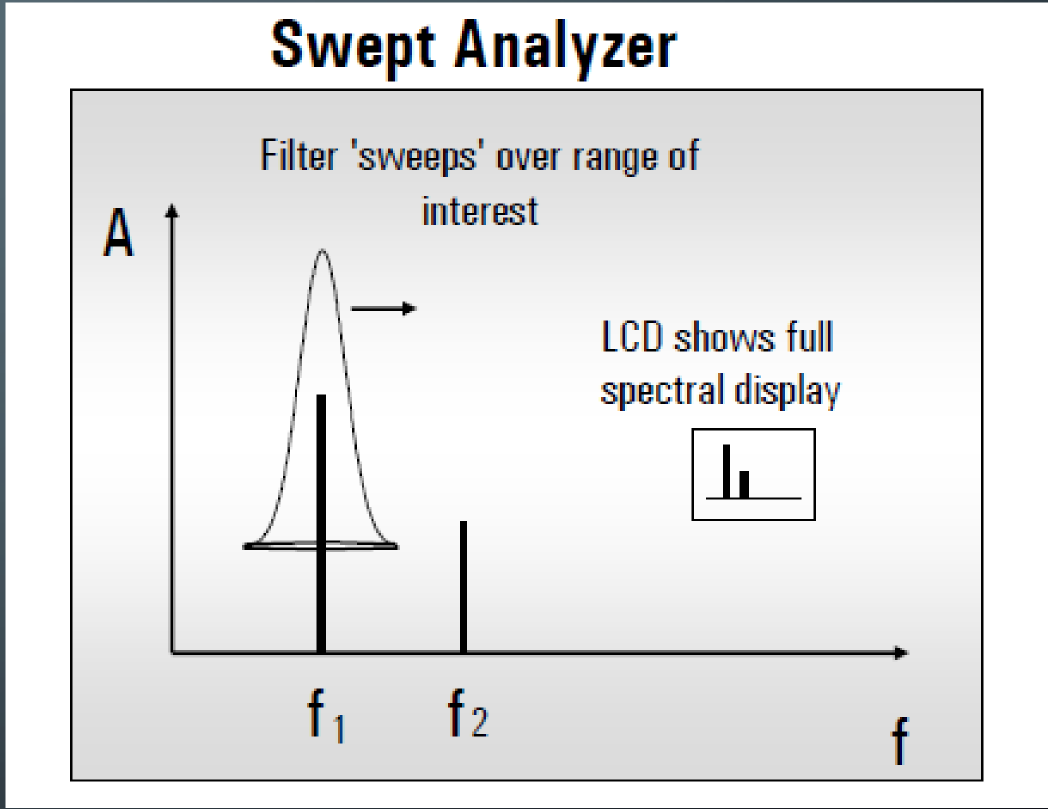
Measure "unknown" signals (in terms of *frequency*)

- Measure signal amplitude characteristics (carrier level, sidebands, harmonics, phase noise etc.)
- Are receivers only (single channel)
- Can be used for scalar components measurements (NO phase) with tracking generator
- Easy to get a trace, much more complicated than a VNA to interpret the results

SPECTRUM ANALYZER (SIGNAL CHARACTERIZATION IN FREQUENCY DOMAIN)

Two main system architectures:



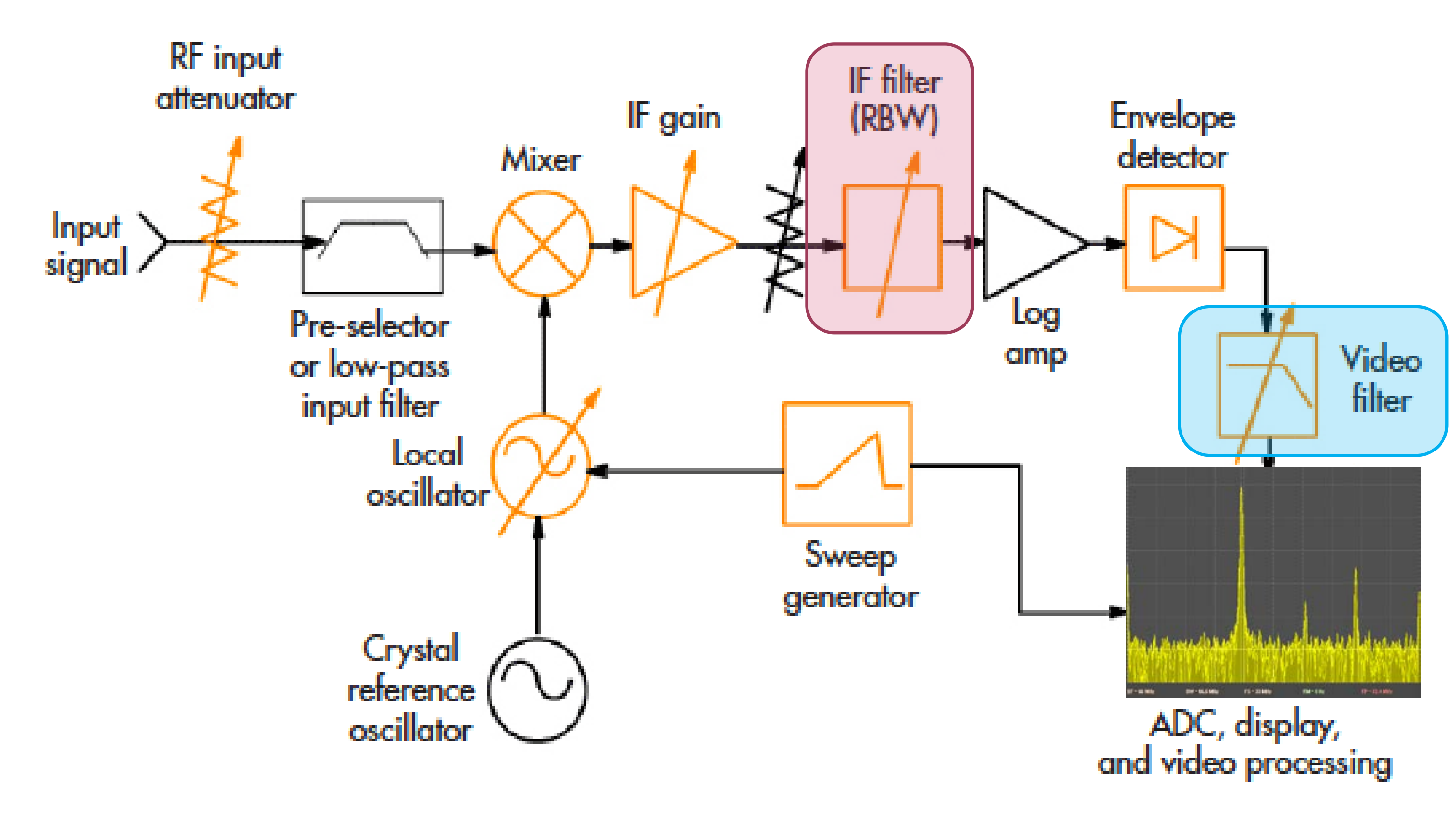


Takes a time-domain signal, digitizes it using digital sampling, then performs the DFT and displays the result. As ADC and DSP technology advances are becoming more prevalent, this architecture is more and more used.

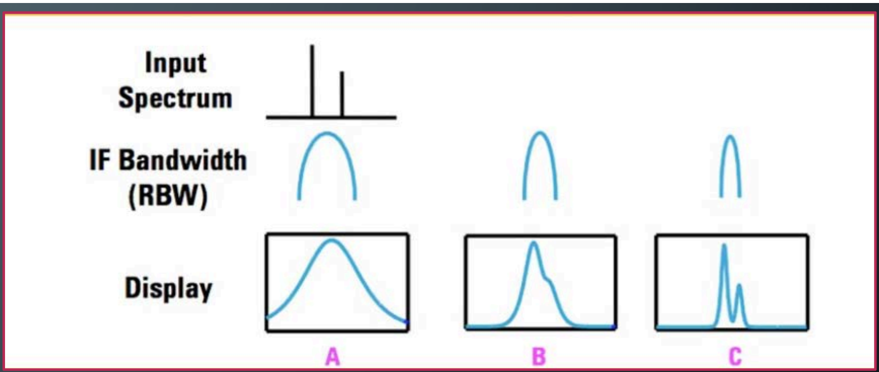
Most common type. These analyzers sweep a reference signal across the frequency range of interest, mixing it with the unknown signal displaying all the frequency components present.

SWEPT ANALYZERS

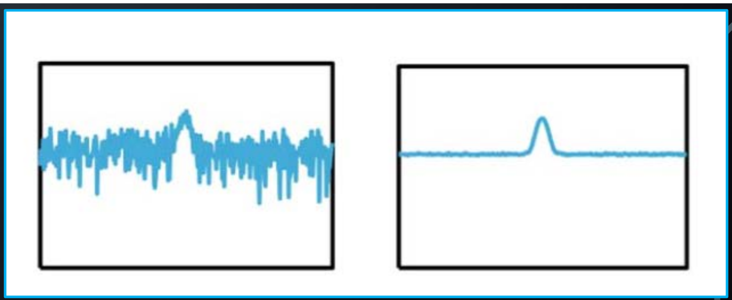
An internal source sweeps a selected frequency range to downconvert and filter the input signal. The IF filter output power reveals the spectral content of the signal at the instantaneous frequency scanned by the instrument.



RBW determines how closely two input signal peaks with comparable amplitudes can be spaced and have the spectrum analyzer resolve the difference between them.



Video BW determines how fast the sweep can go for the data acquisition and display to accurately follow it (trace average/smoothing).

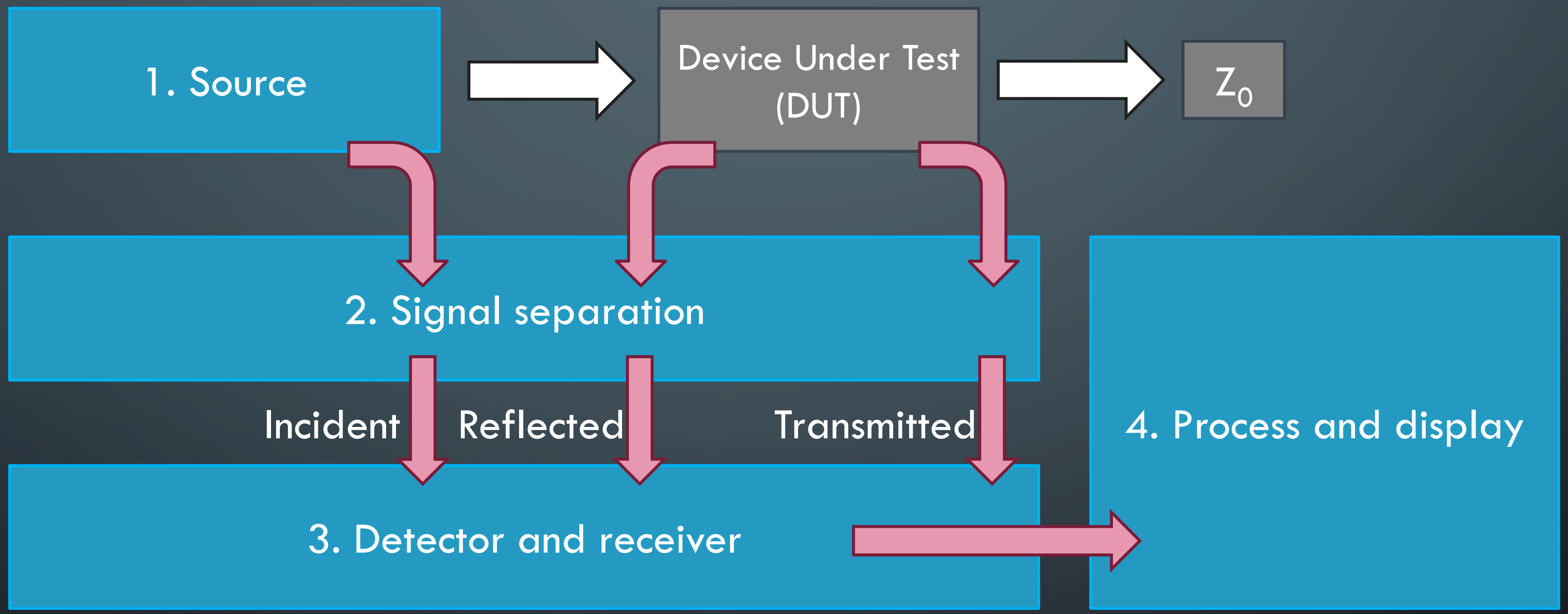


VECTOR NETWORK ANALYZER (VNA)

- Internal description
- Calibration – error matrix
- Practical example: measurement of a filter

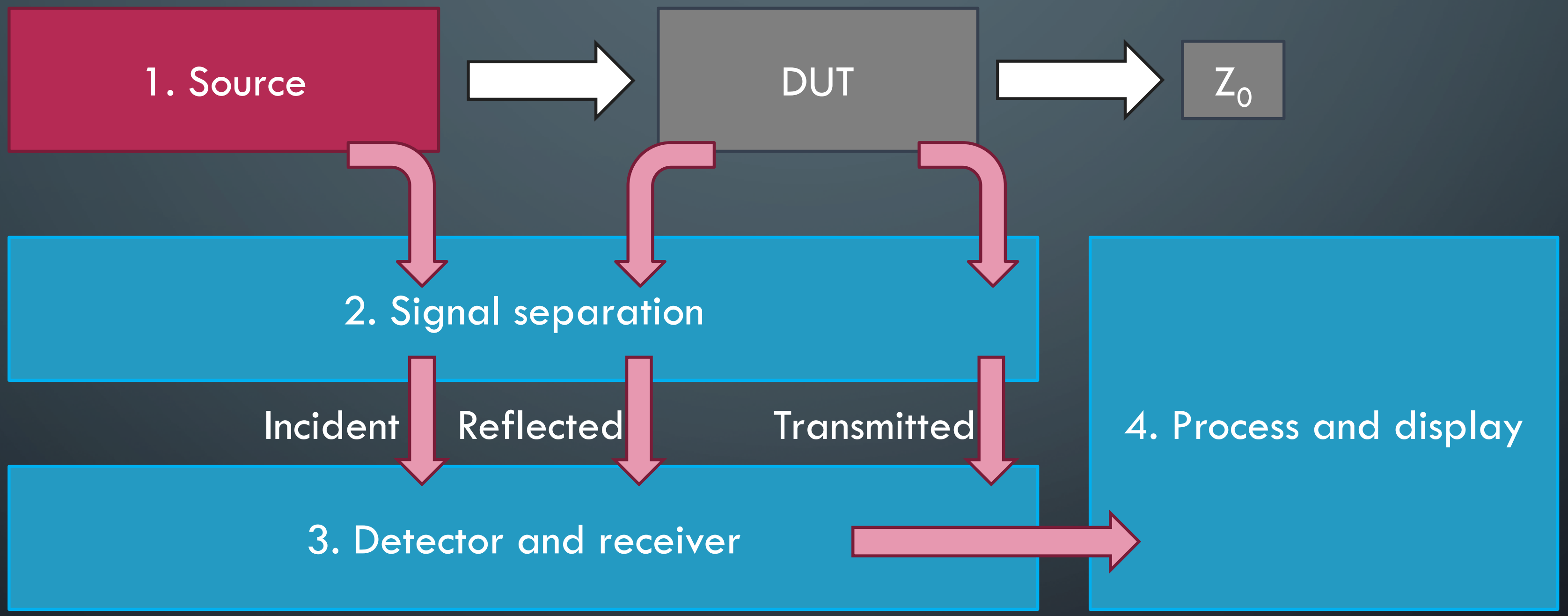
VNA BUILDING BLOCKS

A Vector Network Analyzer measures the scattering matrix elements s_{ij} (i.e. input/output matching and forward/backward transfer function) of a Device Under Test



An internal sine wave source is swept within a given frequency range.
Reflected and transmitted signals are measured and normalized to the source. The direction of the excitation can be inverted.

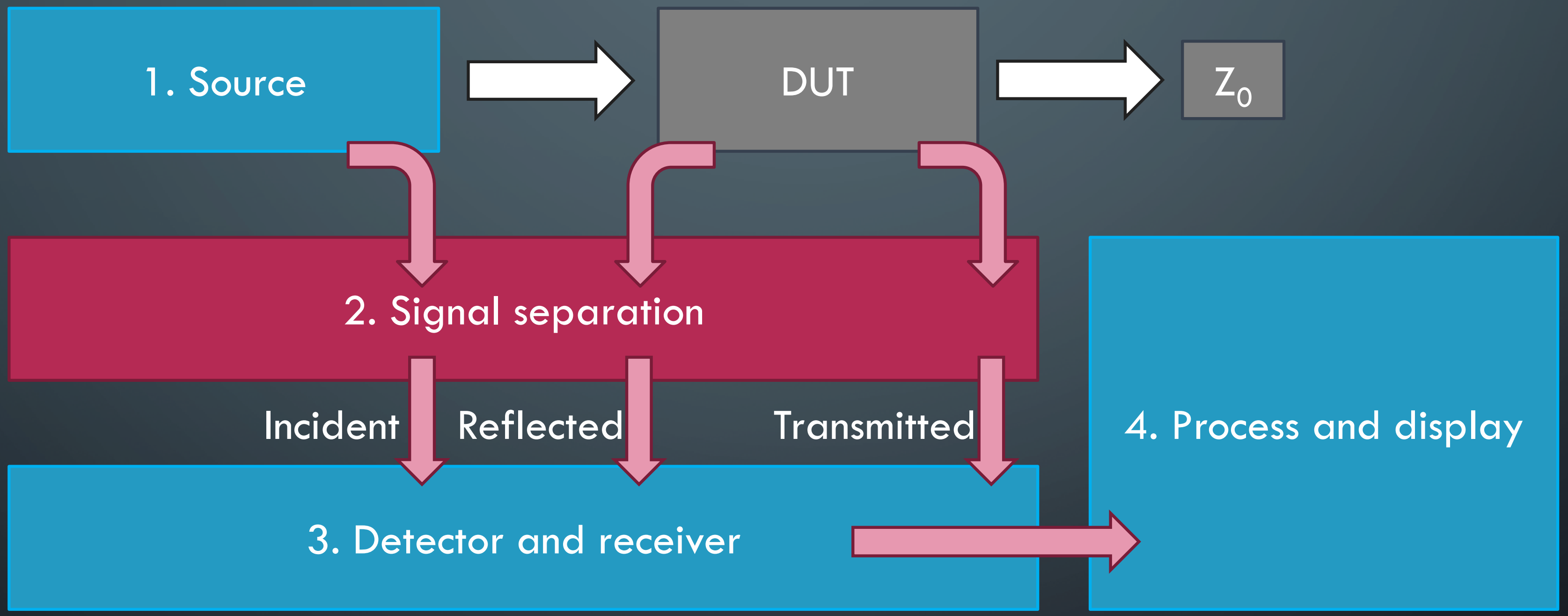
VNA BUILDING BLOCKS



REFERENCE SOURCE

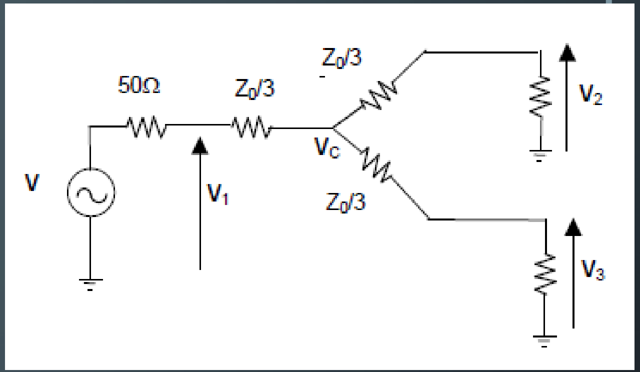
- Supplies stimulus for our “stimulus/response” system
- Either <u>frequency</u> or <u>power</u> sweep (non-linear behavior of amplifiers)
- Either based on open loop VCOs (cheap, high phase noise) or synthesized sweepers (higher performance especially with narrowband components, frequency resolution and stability)
- The majority of network analyzer sold today has integrated, synthesized sources, providing excellent frequency resolution and stability

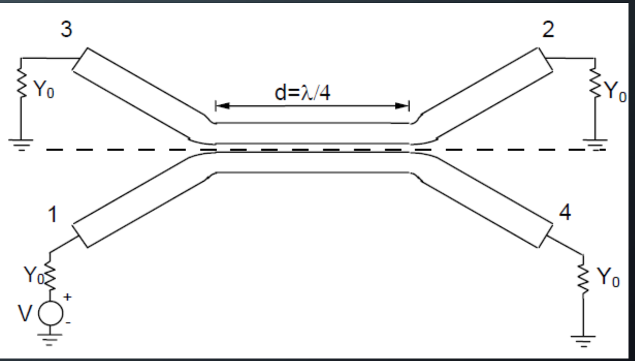
VNA BUILDING BLOCKS



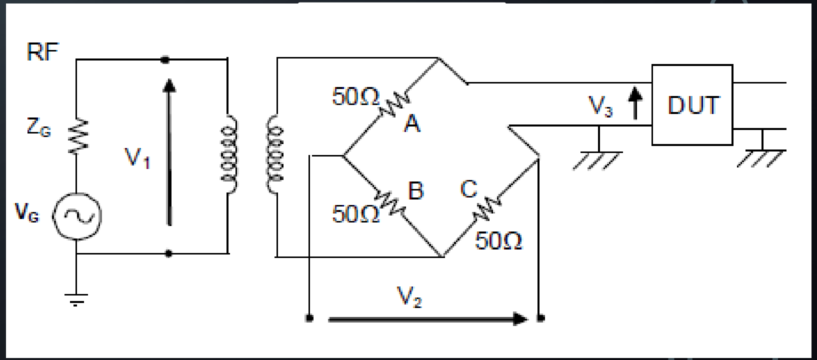
SIGNAL SEPARATION

- Measure a portion of the incident signal to provide a reference for ratioing
  - Resistive splitters
    - Non directional, broadband
    - > 6 dB insertion loss on each arm
  - Directional couplers
    - Low insertion loss, good isolation and directivity
    - Widely used in the microwave, high pass response makes them unusable below 40 MHz

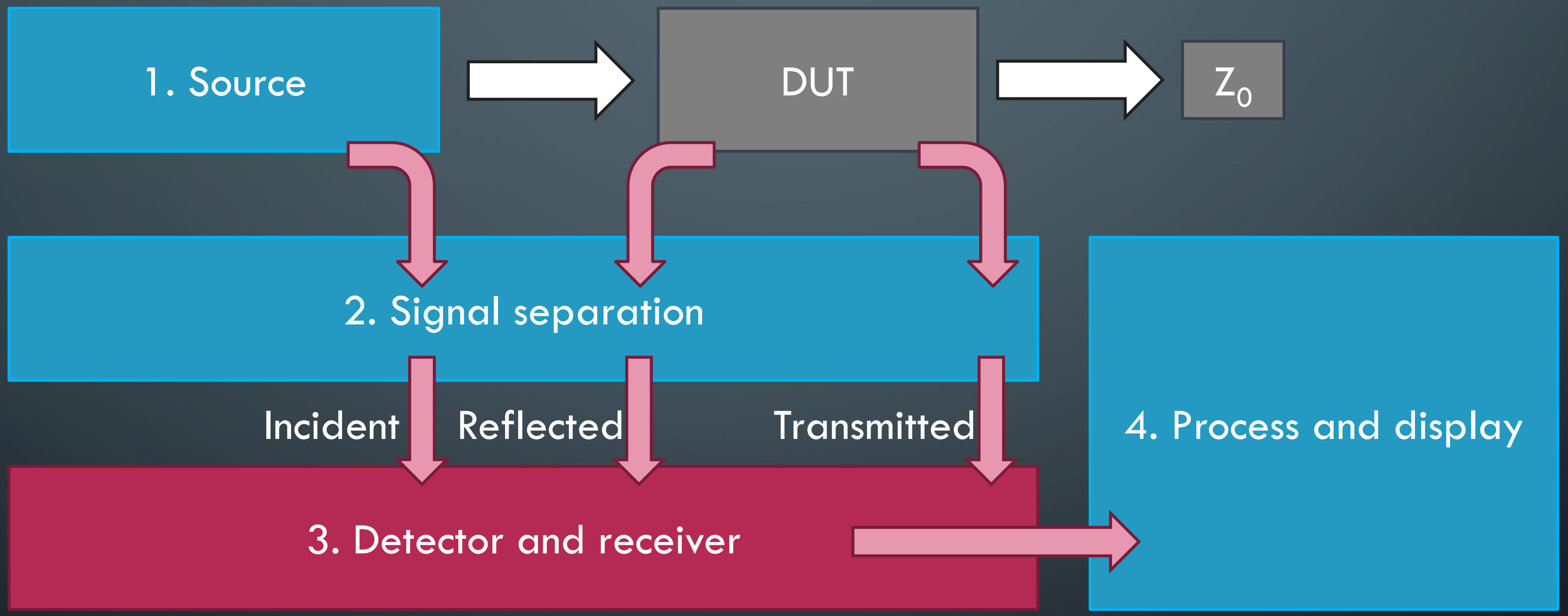




- Separate forward and reflected travelling waves at the input of the DUT
  - Directional couplers are again ideal components due to their isolation, directivity and low insertion loss
  - However, due to the difficulty to make them broadband, bridges are often used (DC, higher losses)

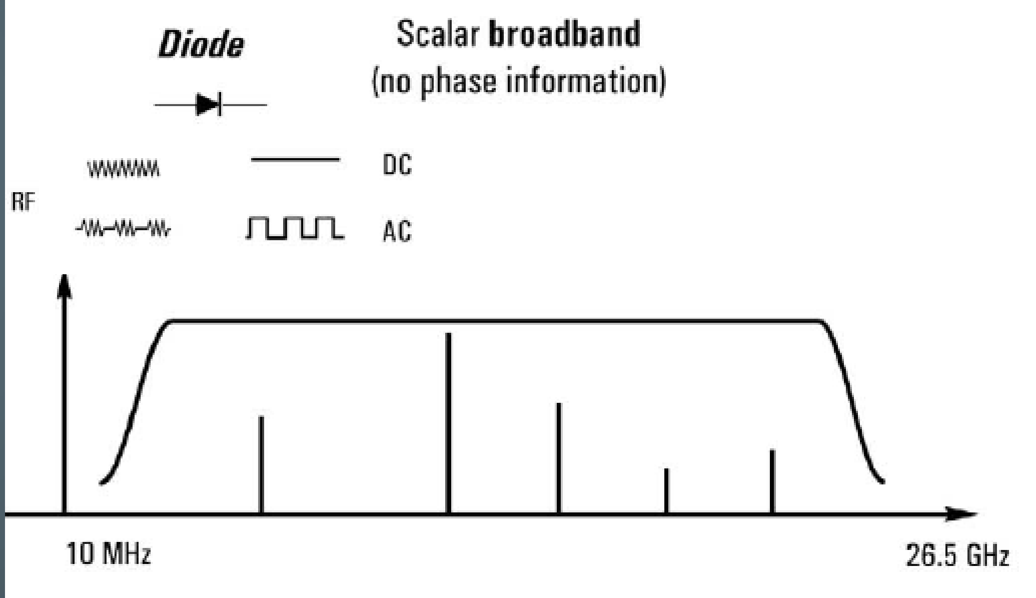


VNA BUILDING BLOCKS

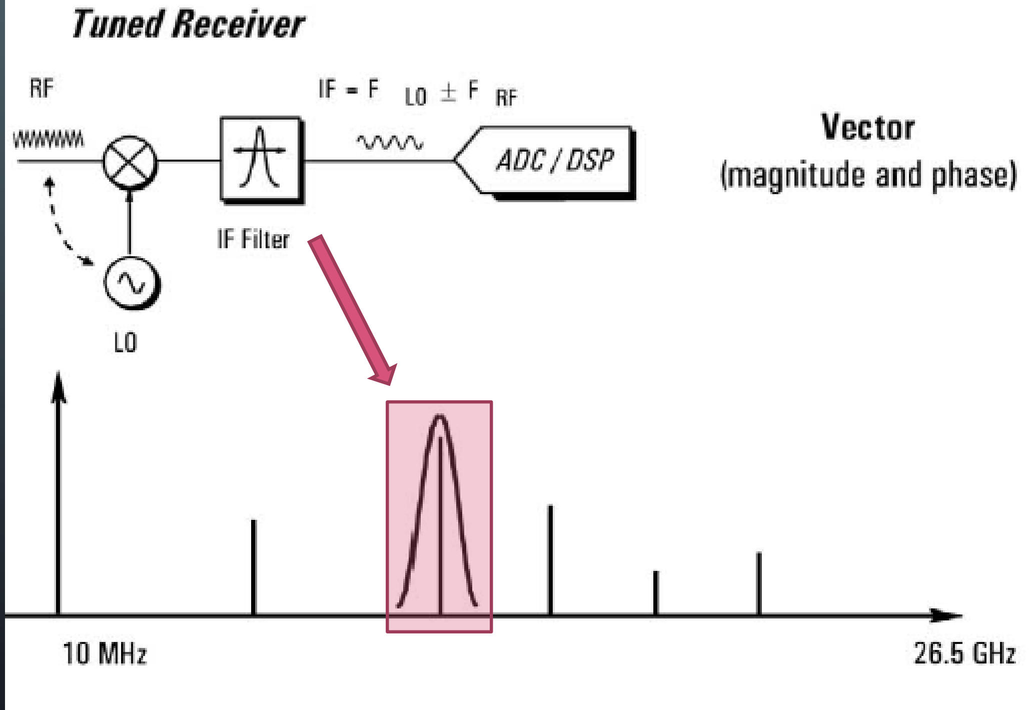


DETECTOR AND RECEIVER

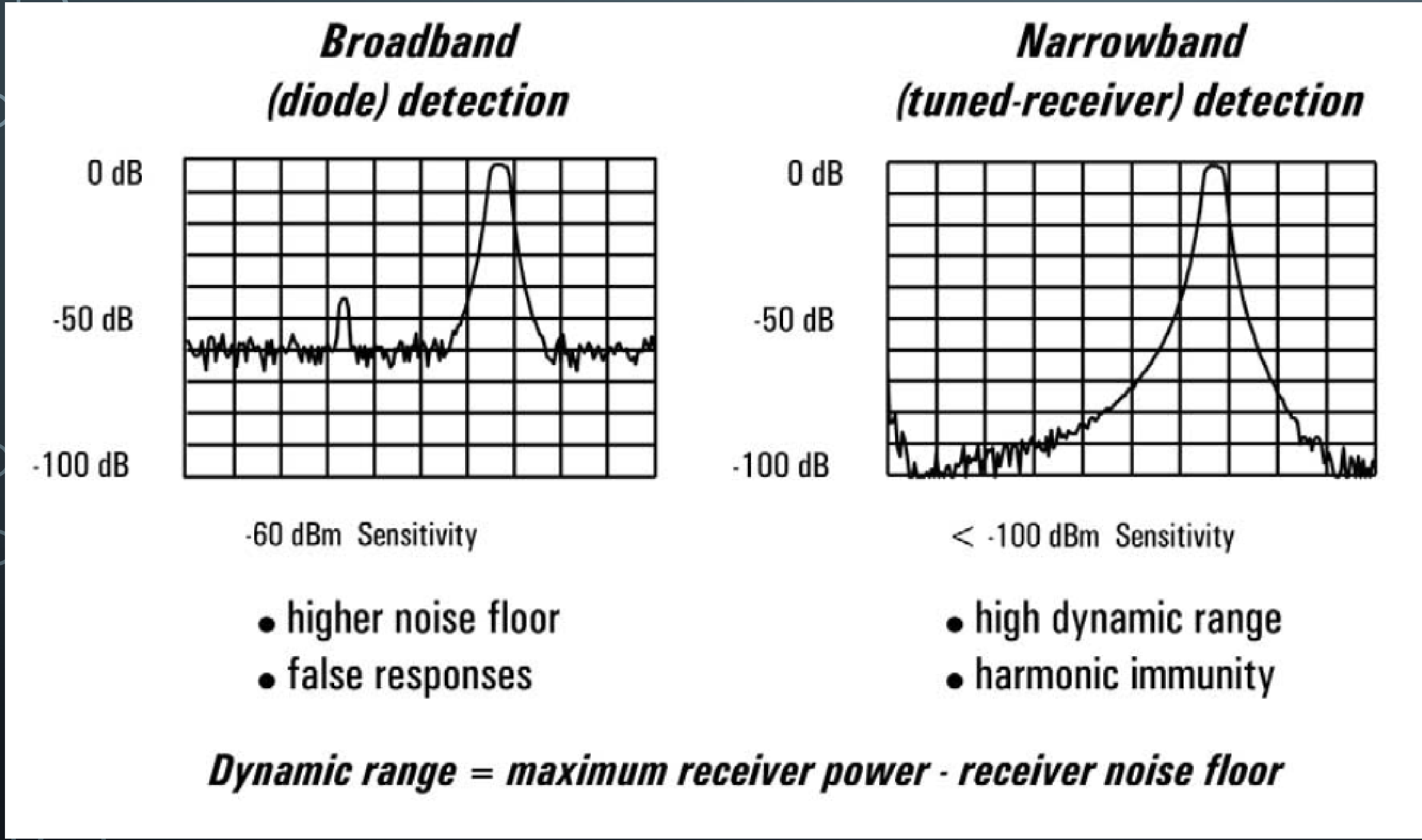
- Direct detection (scalar)
  - Peak detector (RF diodes)
  - Broadband (typically from 10 MHz to 30 GHz), low-cost
  - Dynamic range of the order of 60 dB
  - Sensitive to source harmonics and other spurious signals



- Tuned Receiver (vector – super heterodyne)
  - Uses a local oscillator (LO) to mix the RF down to a lower intermediate frequency (IF)
  - The IF signal is bandpass filtered (narrows the bandwidth and improves the sensitivity and dynamic range)
  - By means of ADC and DSP to extract magnitude and phase information from the IF signal.
  - Tuner-receiver approach is used in vector network analyzers and spectrum analyzers

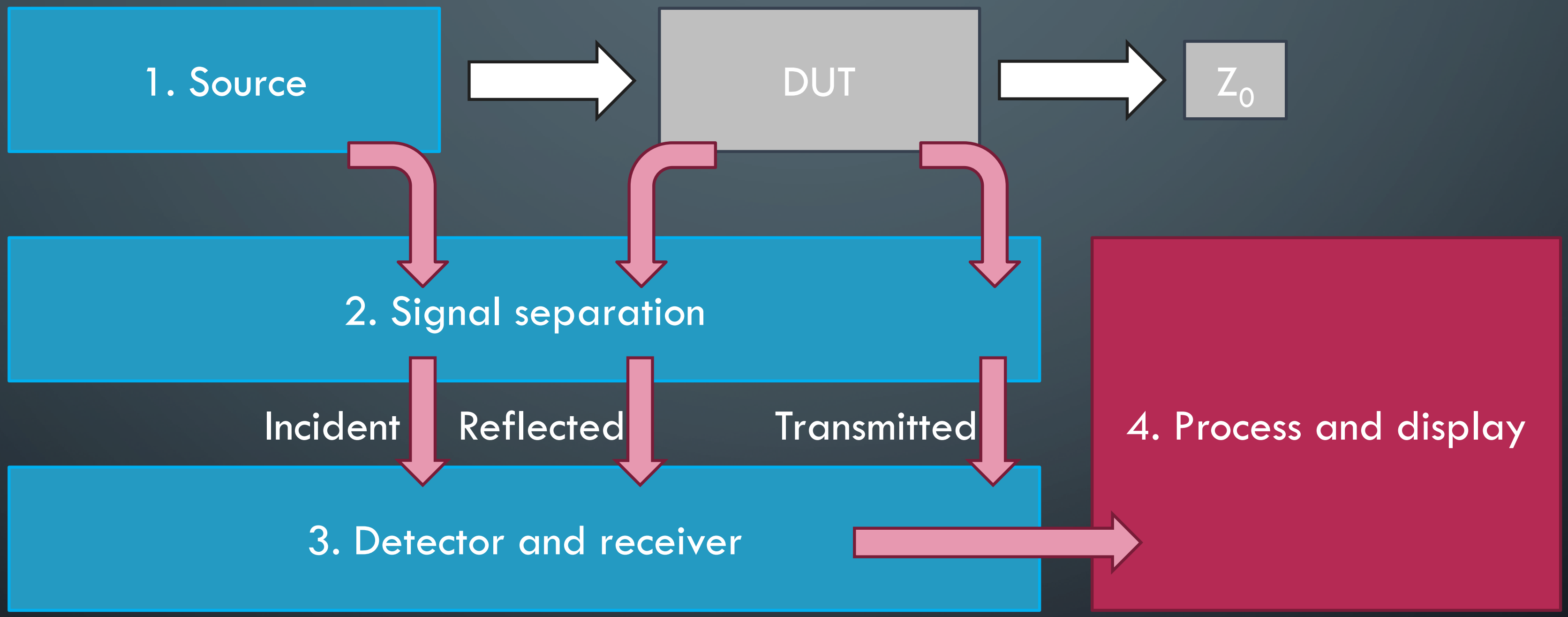


DETECTION SCHEMES COMPARISON



- Dynamic range is defined as the maximum power the receiver can accurately measure minus the receiver noise floor
- Many applications require a high dynamic range: e.g. measurement of a filter stopband performance
- Notice that the filter exhibit 90 dB of rejection, which is not measurable with the scalar detection (due to the higher noise floor)
- Scalar detection prone to false responses: e.g. a harmonic of the source might fall in the passband of the filter. The detector will register a response even though the stopband is attenuating the frequency of the fundamental. In a tuned receiver such signal would be filtered away and would not appear on the display
- Source sub-harmonics and spurious outputs can also cause false display responses

VNA BUILDING BLOCKS



PROCESS AND DISPLAY

- Instrument set-up
  - Power, frequency, IF filter, number of points, averages
- Various formatting modes:
  - Linear and log sweeps
  - Linear and log formats
  - Polar plots
  - Smith charts
- Trace markers
- Limit lines
- Internal measurements automation (save/recall state)
- PC compatible programs used to automate measurements and create intuitive GUI (LabView)

MEASUREMENT ERROR SOURCES

Three basic sources of measurement error

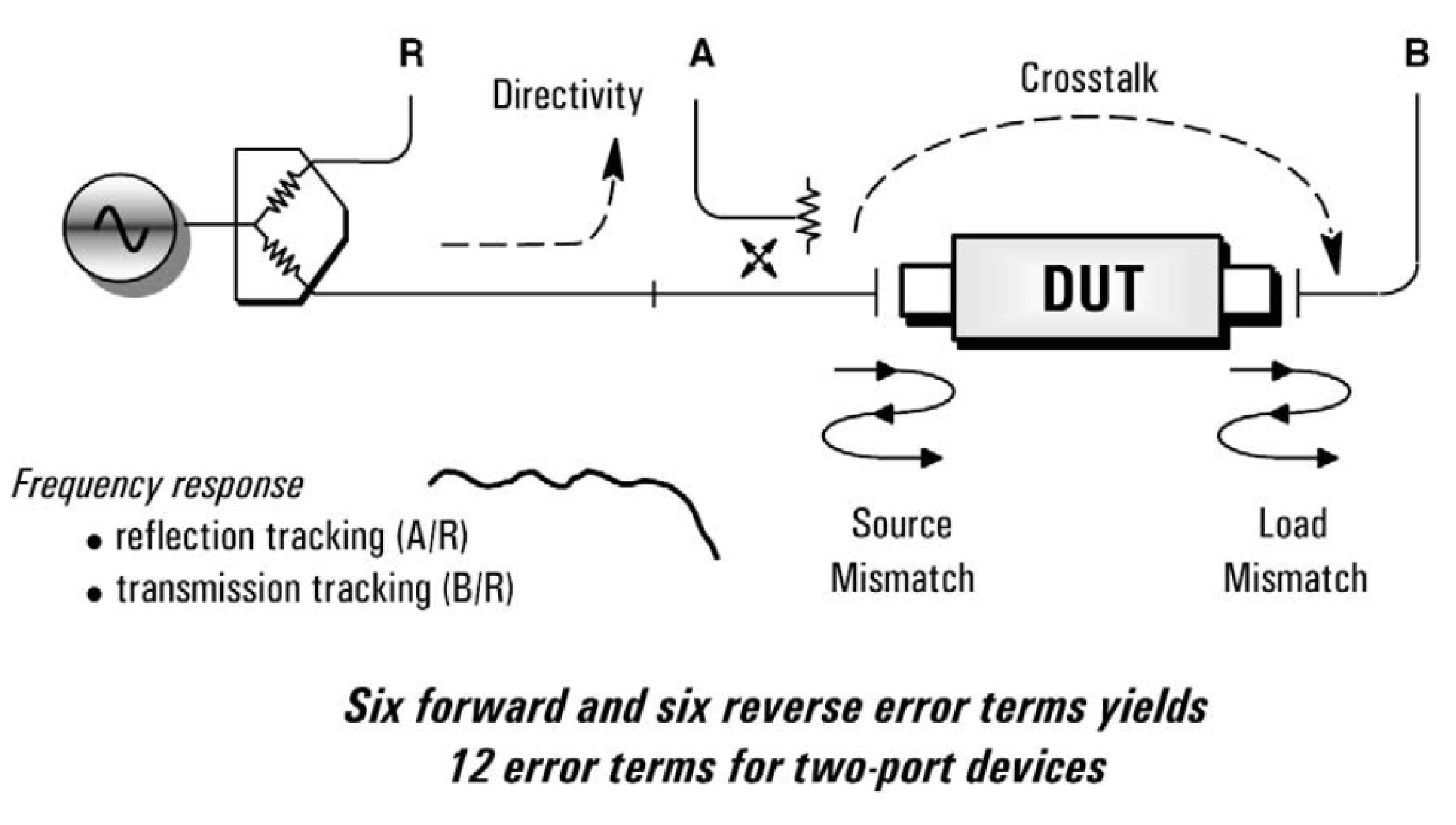
- Systematic:
  - Due to imperfections in the analyzer and test setup
  - Repeatable (and therefore predictable), time invariant
  - Characterized during calibration process and mathematically removed during measurements
- Random
  - Unpredictable (they vary with time in a random fashion)
  - Cannot be removed by calibration
  - Main contributors: switch and connector repeatability, instrument noise (source phase noise, sampler noise, IF noise)
- Drift
  - Instrument or test system performance changing AFTER a calibration has been done
  - Primarily caused by temperature variation
  - Can be removed by further calibrations
  - The timeframe over which a calibration remains accurate depends on the rate of drift in the test environment
  - Usually, providing a stable ambient temperature is sufficient to minimize drift errors

Calibration

Cannot be removed

Re-calibration or temperature stabilization

SYSTEMATIC MEASUREMENT ERRORS



3 categories of errors:

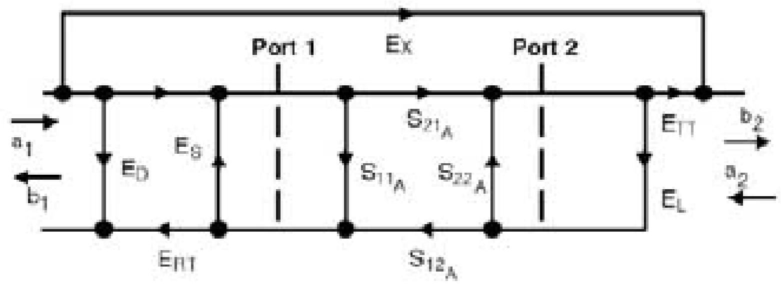
- Signal leakage:
  - Directivity
  - Crosstalk
- Signal reflections:
  - Source match
  - Load match
- Receiver frequency response:
  - Reflection tracking
  - Transmission tracking
- The full 2 port error model includes all six terms for the forward and six terms for the reverse direction

TYPES OF ERROR CORRECTION

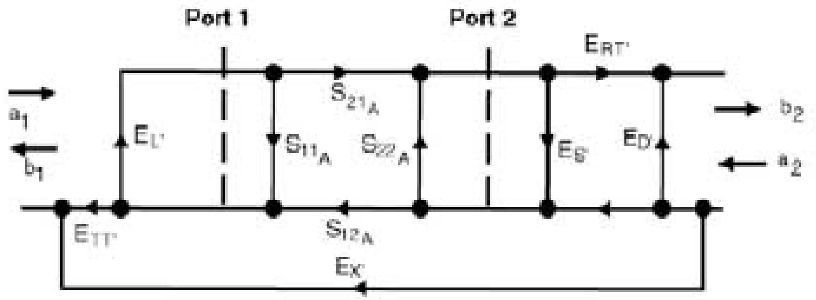
- Response (normalization)
  - Simple to perform (direct connection of network analyzer's ports)
  - Only corrects for tracking errors
  - Stores reference trace in memory, then it calculates data/memory
- Vector
  - Requires measurement of multiple standards (open, short, load, thru)
  - Requires an analyzer that can measure both magnitude and phase (VNA)
  - Accounts for all major sources of systematic error
  - 1-port calibration:
    - Used for reflection measurement
    - Can correct only 3 terms (directivity, source match and reflection tracking)
  - Full 2-port calibration:
    - Used both for reflection and transmission measurements
    - 12 systematic error terms are measured and removed
    - Ususally require 12 measurements on 4 known standards (thru, open, short, match - TOSM)
    - The electrical lengths of each standard are defined in a calibration kt file, stored in the network analyzer

2-PORT ERROR MODEL

Forward model



Reverse model



E_D = fwd directivity	E_L = fwd load match
E_S = fwd source match	E_{TT} = fwd transmission tracking
E_{RT} = fwd reflection tracking	E_X = fwd isolation
$E_{D'}$ = rev directivity	$E_{L'}$ = rev load match
$E_{S'}$ = rev source match	$E_{TT'}$ = rev transmission tracking
$E_{RT'}$ = rev reflection tracking	$E_{X'}$ = rev isolation

$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

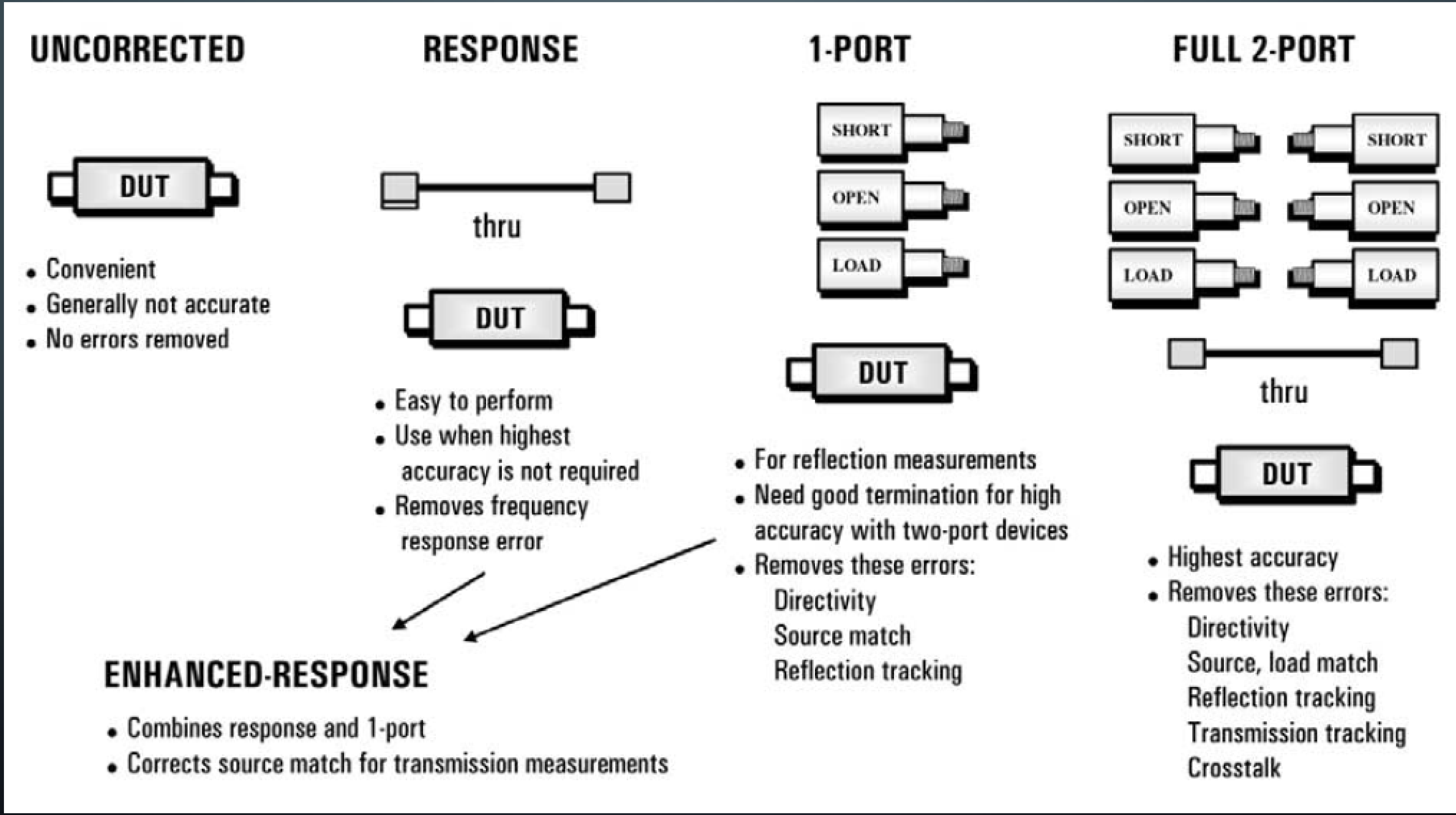
$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{RT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)-E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

- Each actual S-parameter is function of all four measured S-parameters
- VNA must make a forward and reverse sweep to update any one S-parameter
- Luckily you don't need to know these equations to use a network analyzer!!!

SUMMARIZING…



REFERENCES

[1] Keysight Technologies website:

www.keysight.com

[2] Keysight techincal notes:

www.keysight.com/main/facet.jspx?t=79831.g.1&cc=IT&lc=ita&sm=g